On the role of cloud radiative-dynamical feedbacks on the regional response of precipitation to climate change

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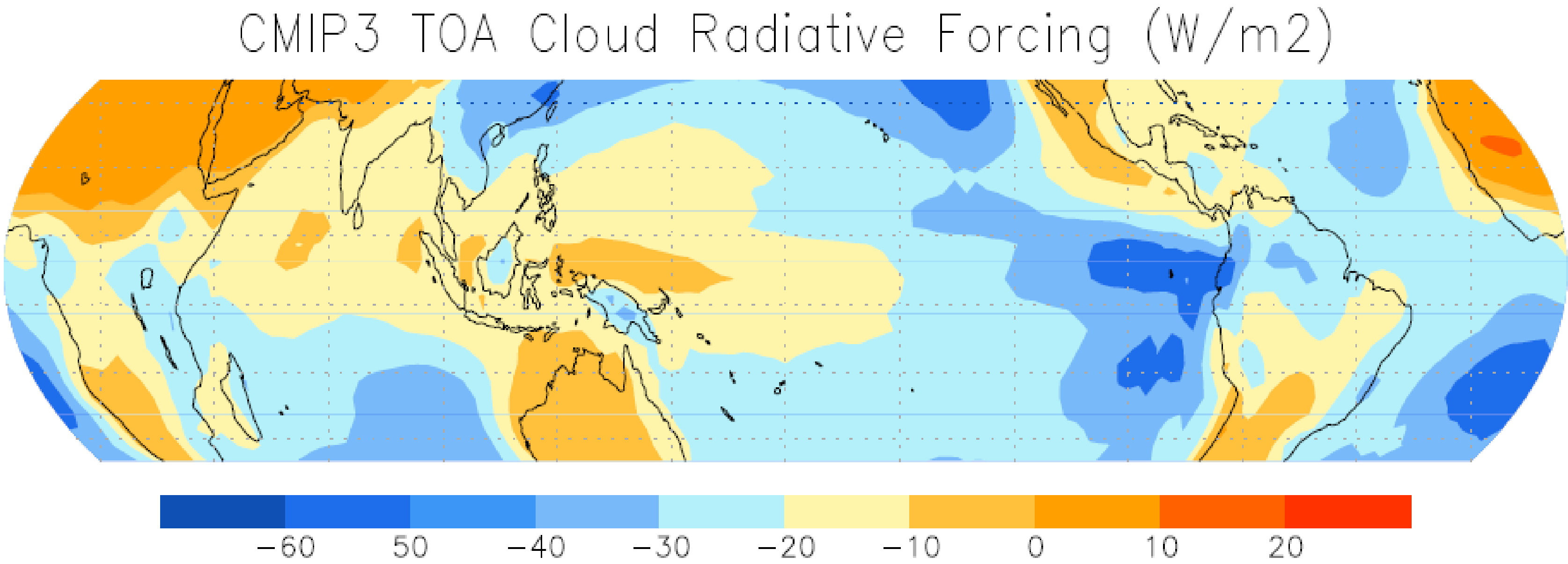
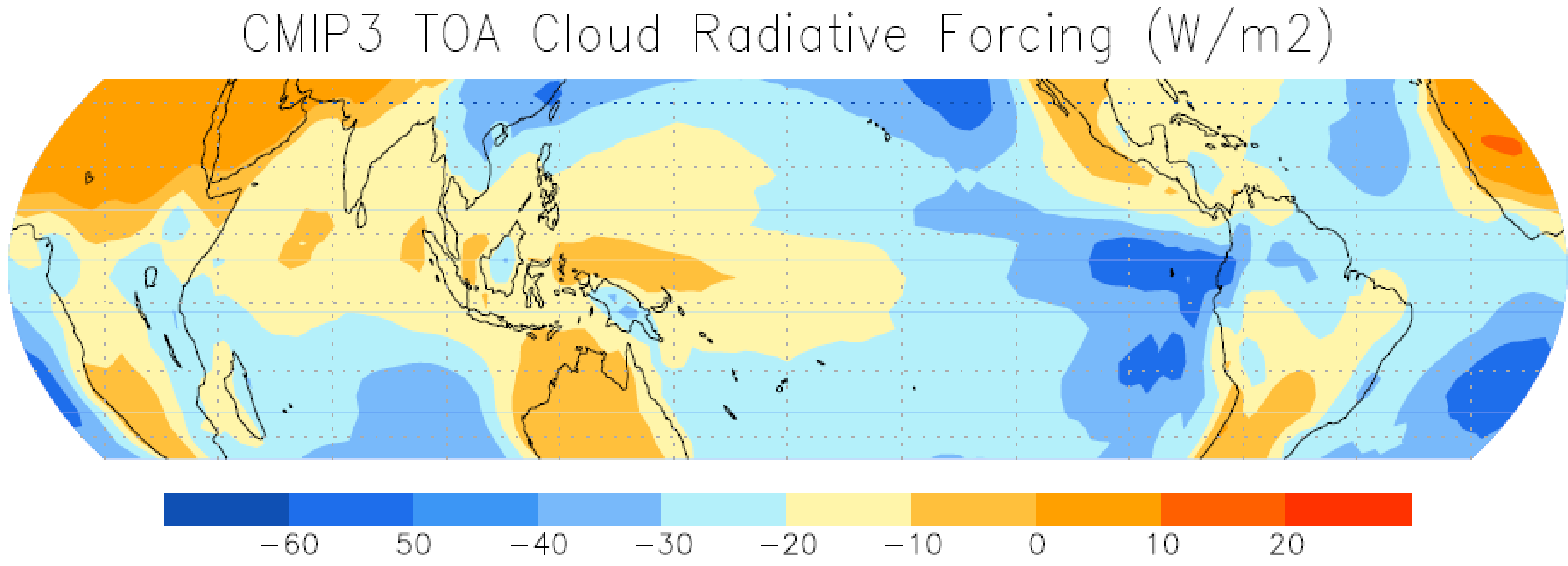
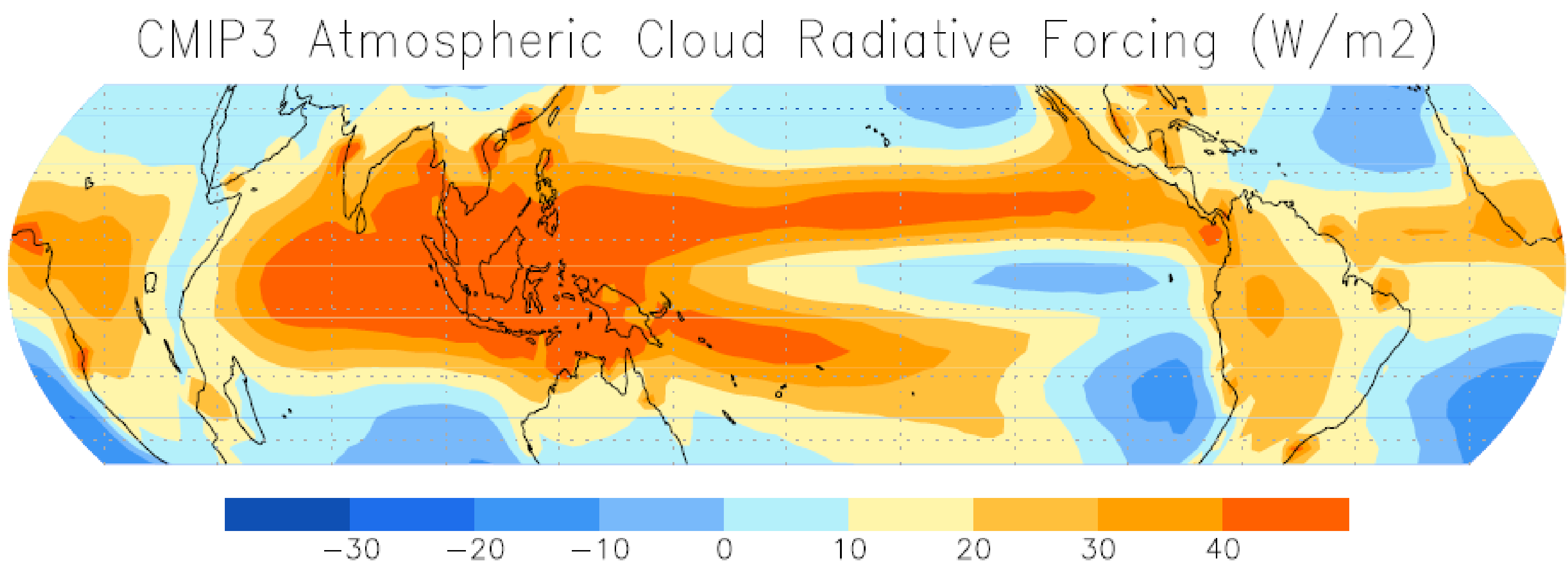

CMIP3 TOA Cloud Radiative Forcing (W/m2)
−60
50
−40
−30
−20
−10
0
10
20

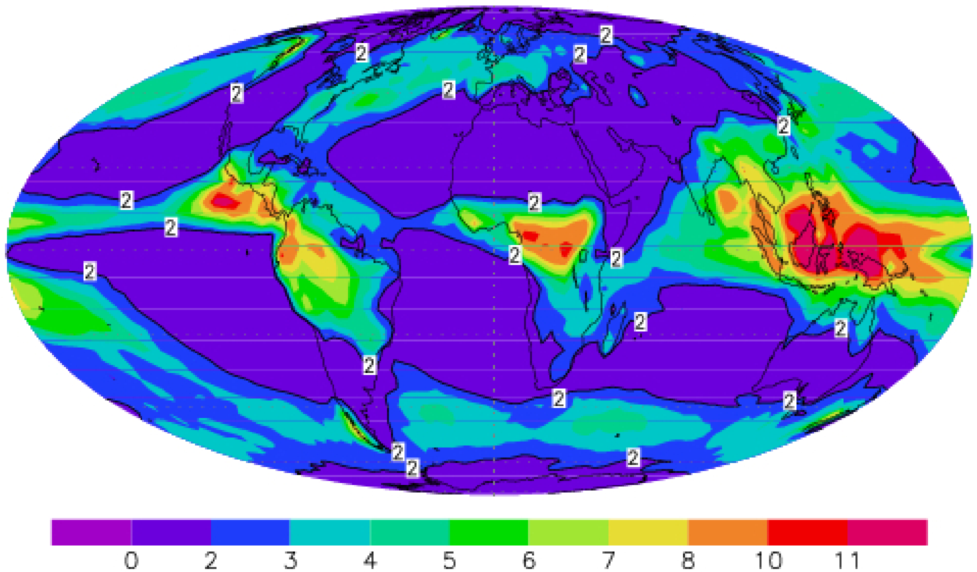




$$ACRF = CRF_{TOA} - CRF_{SFC}$$

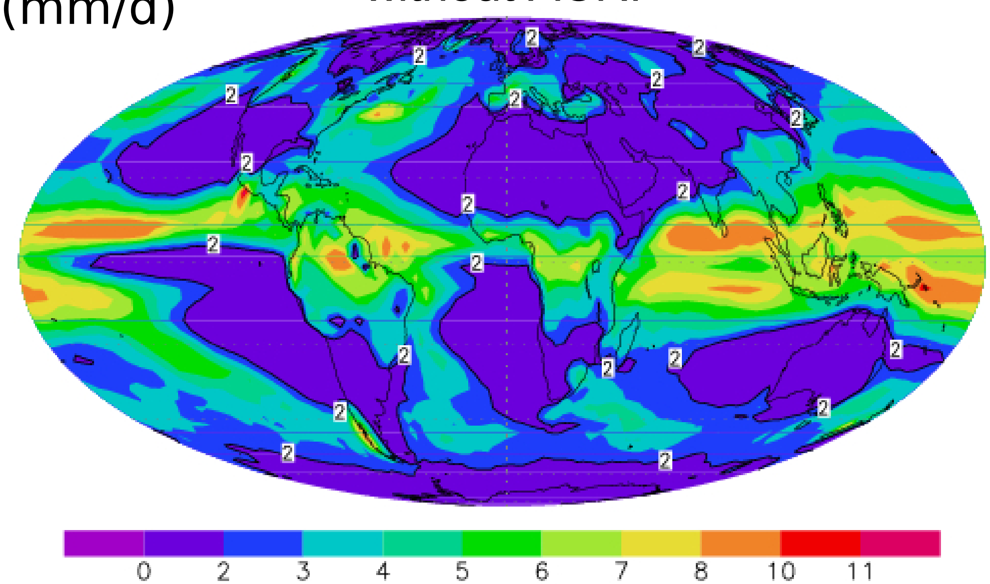
Impact of the Atmospheric Cloud Radiative Forcing on GCM-simulated tropical circulation and precipitation

with ACRF

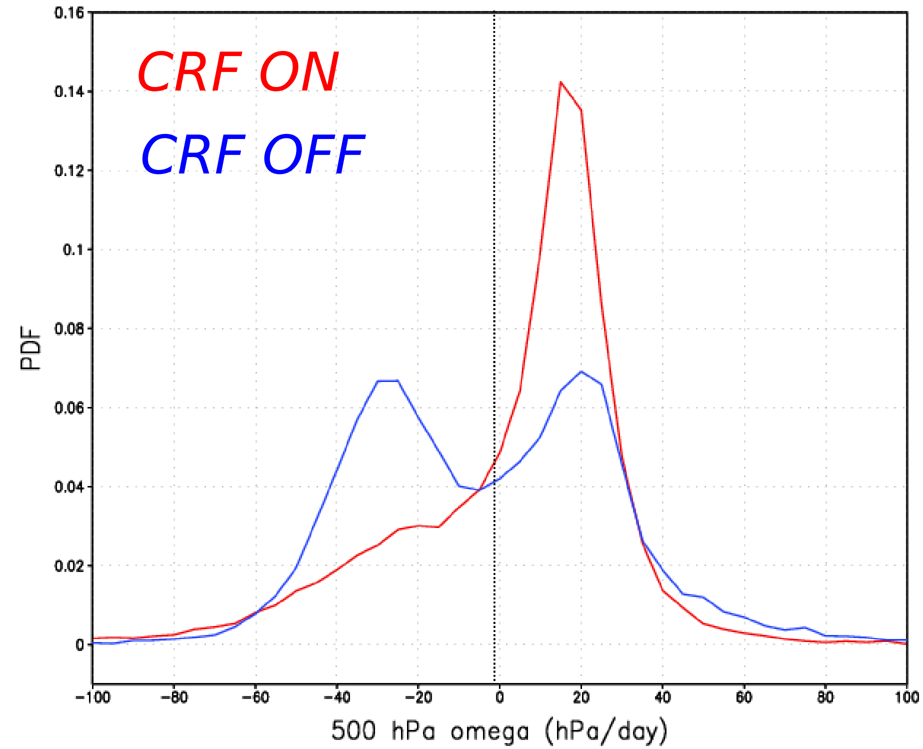


Precipitation (mm/d)

without ACRF



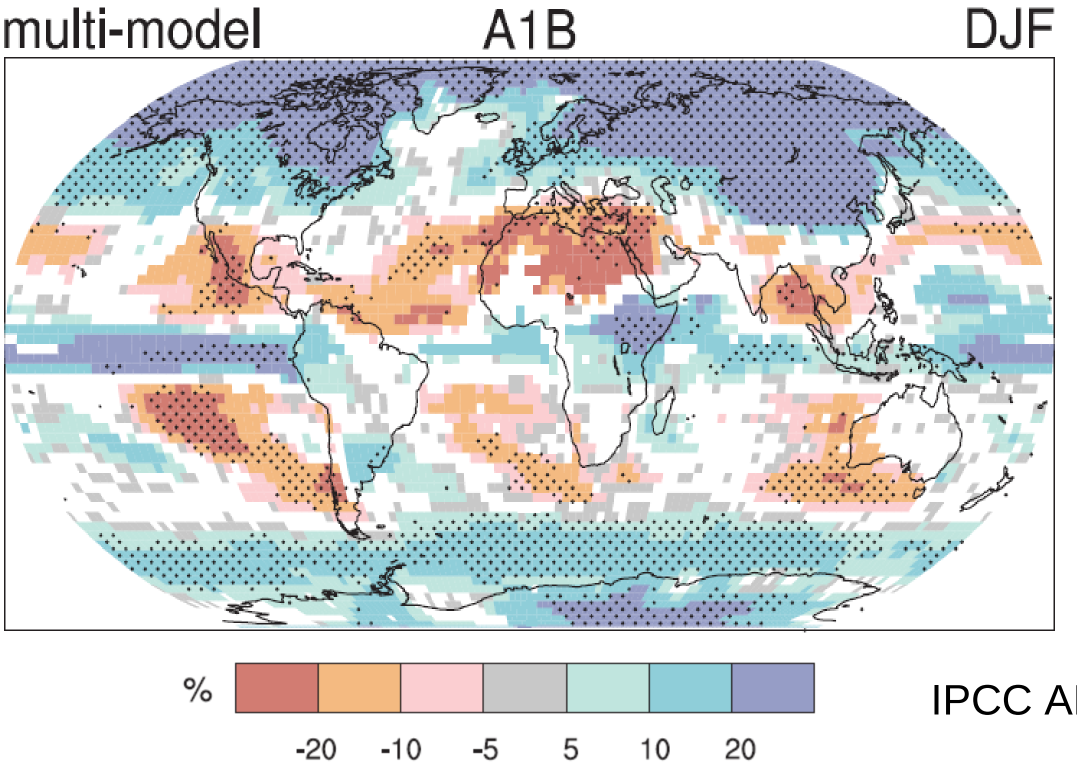
PDF of 500hPa omega



Cloud-radiative effects strengthen the Hadley-Walker circulation and make the ITCZ more narrow

cf Slingo & Slingo 1988, Randall et al. 1989; etc

Regional response of precipitation to climate change



IPCC AR4 (2007)

What is the impact of changes in cloud-radiative forcing on precipitation ?

What controls the response of tropical precipitation to climate change ?

Water budget :

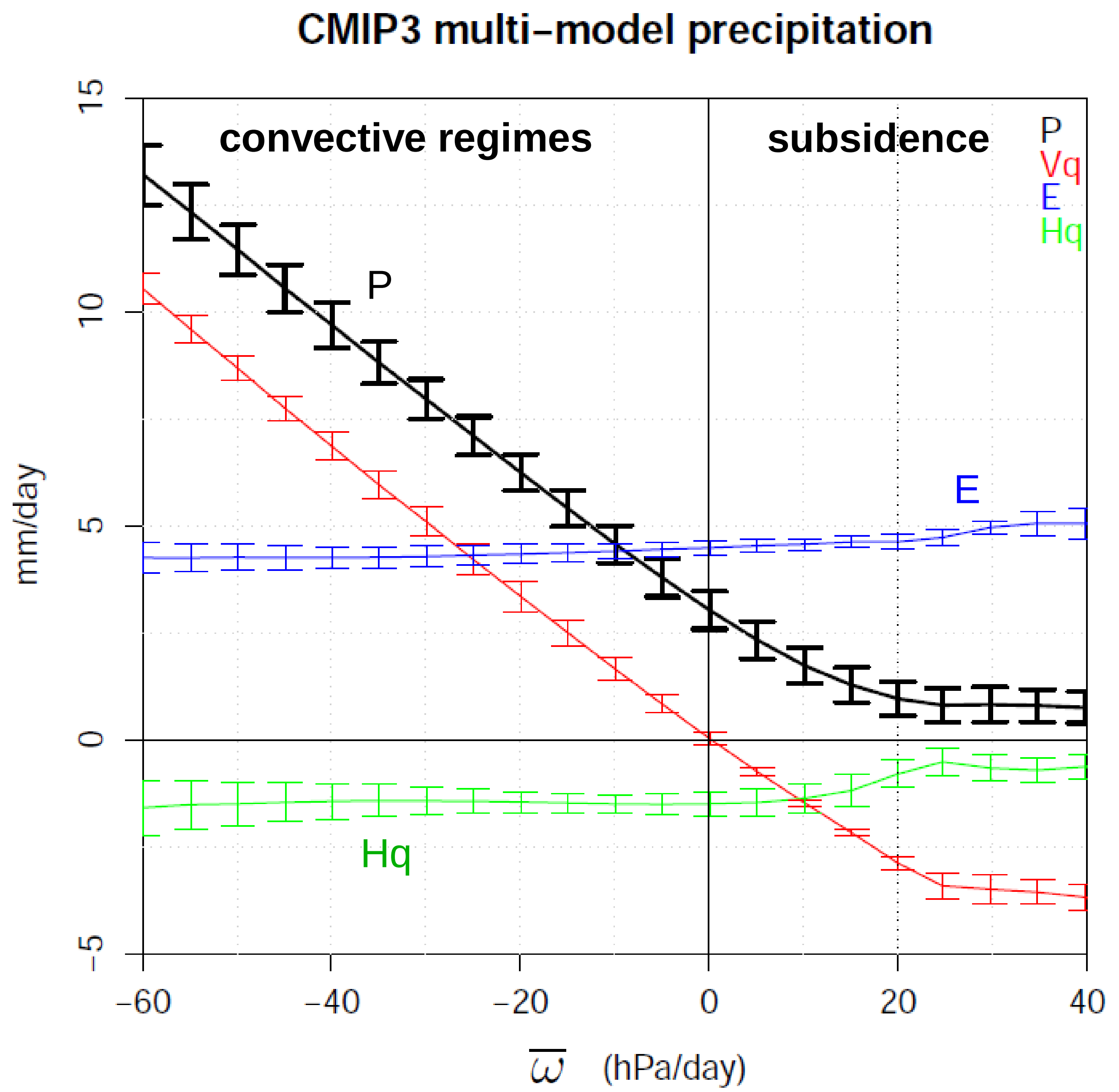
$$P = E - \left[\omega \frac{\partial q}{\partial P}\right] + H_q$$

Water budget : $P = E - \left[\omega \frac{\partial q}{\partial P}\right] + H_q$

- Prominent role of the vertical advection term

- What change under global warming ?

→ Clausius-Clapeyron
→ shape of ω profile



Analysis Method

$$P = E - \left[\omega \frac{\partial q}{\partial P} \right] + H_q$$

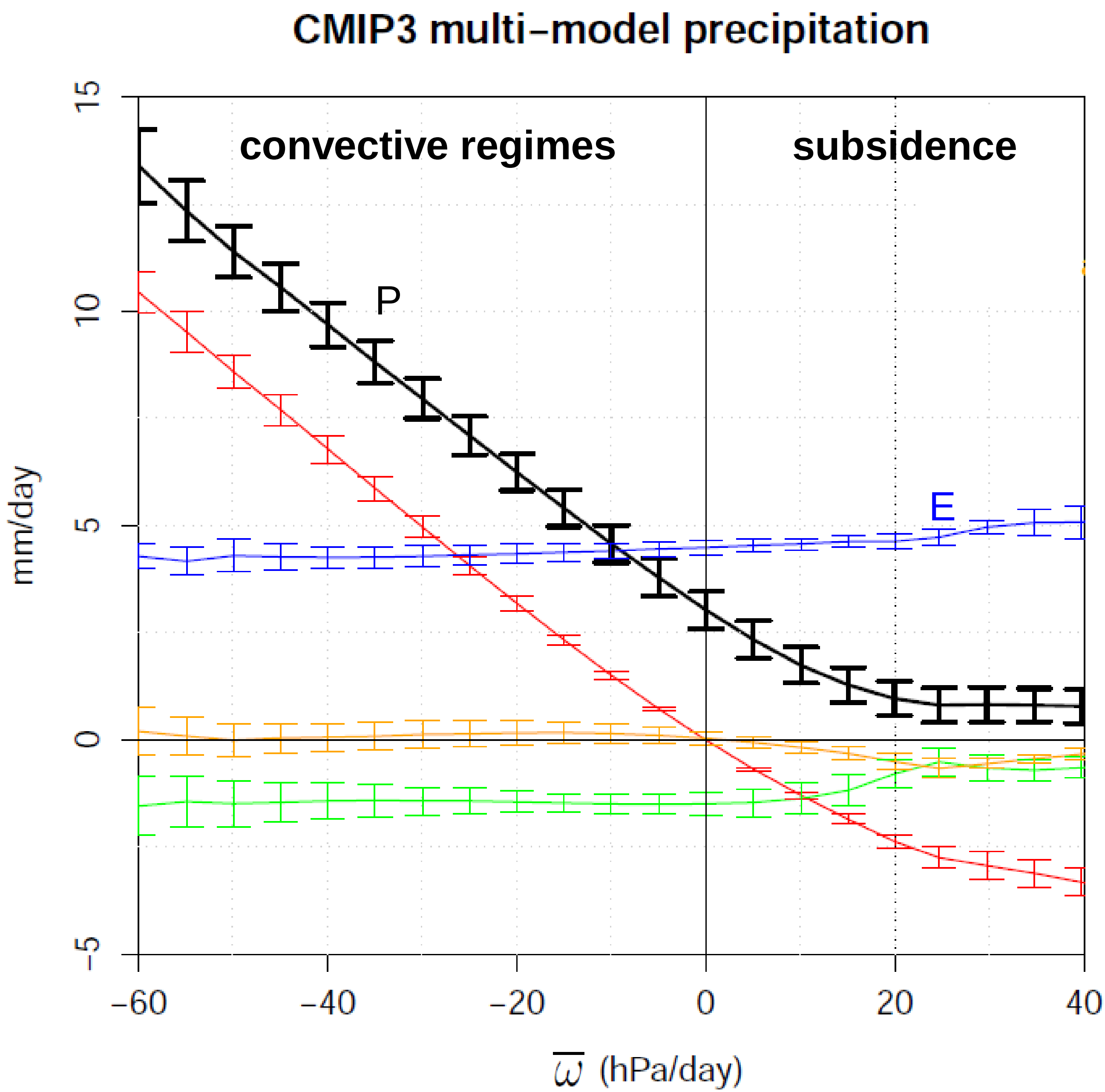
- Let's characterize the $\omega(P)$ profile by :
  - $\overline{\omega} = [\omega]$ (mass-weighted vertical average)
  - vertical structure

- In the Tropics, the vertical structure of ω is close to a first baroclinic mode (i.e. max in mid-troposphere)

- Let's compare the actual $\omega(P)$ profile with a vertical profile $\Omega(P)$ that would have the same vertical average ($\overline{\Omega} = \overline{\omega}$) but a prescribed (1st baroclinic) vertical structure $\psi(P)$ such as $\Omega(P) = \overline{\omega}\,\psi(P)$.
  Then $\omega(P)$ can be expressed as : $\omega(P) = \Omega(P) + \{\,\omega(P) - \Omega(P)\,\}$

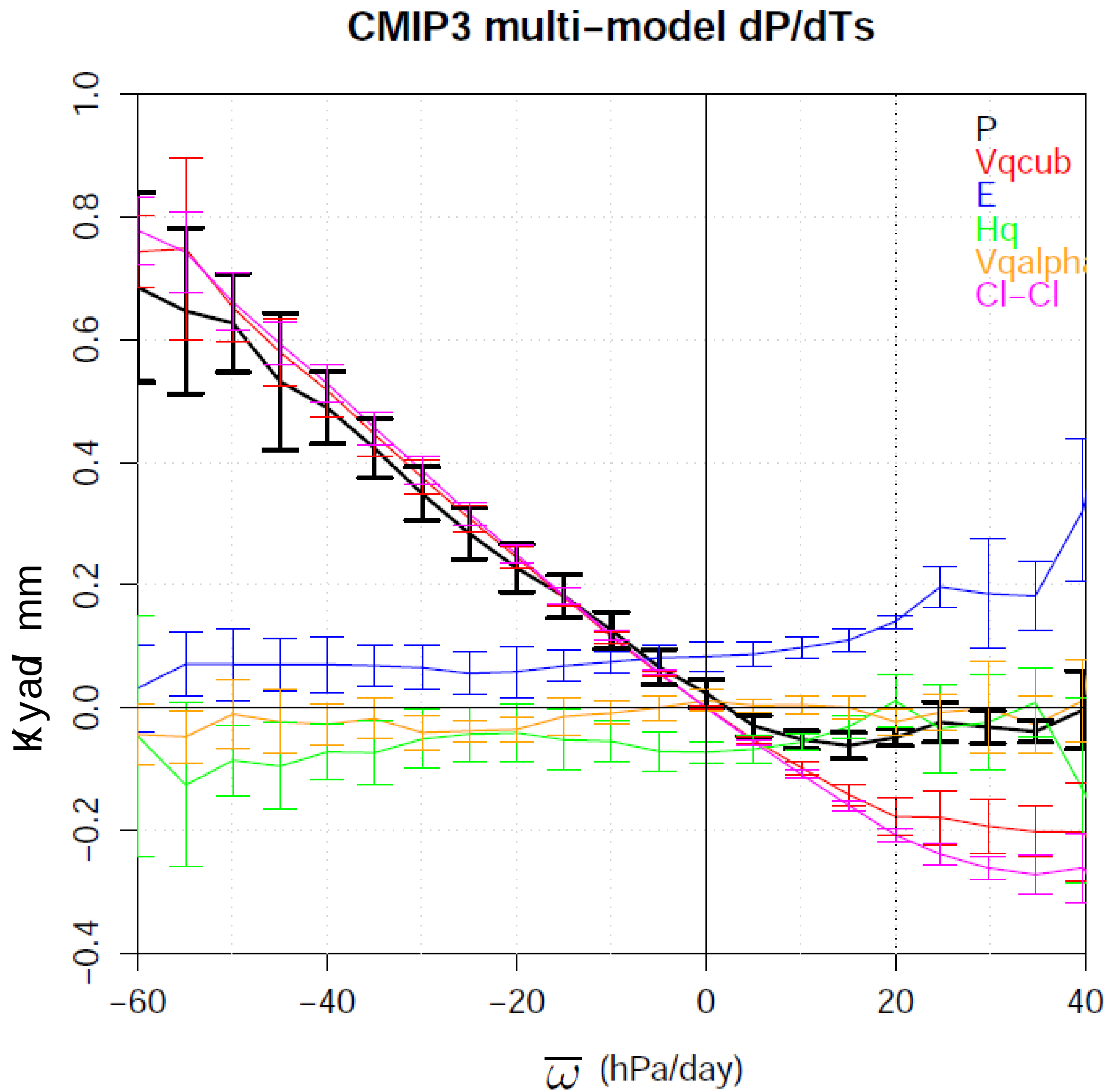
Then $P = E + \overline{\omega}\,\Gamma_q + H_q + V_q^{\alpha}$ with $\Gamma_q = -\left[\psi(P)\, \frac{\partial q}{\partial P} \right]$

$$P = E + \overline{\omega}\,\Gamma_q + H_q + V_q^{\alpha}$$



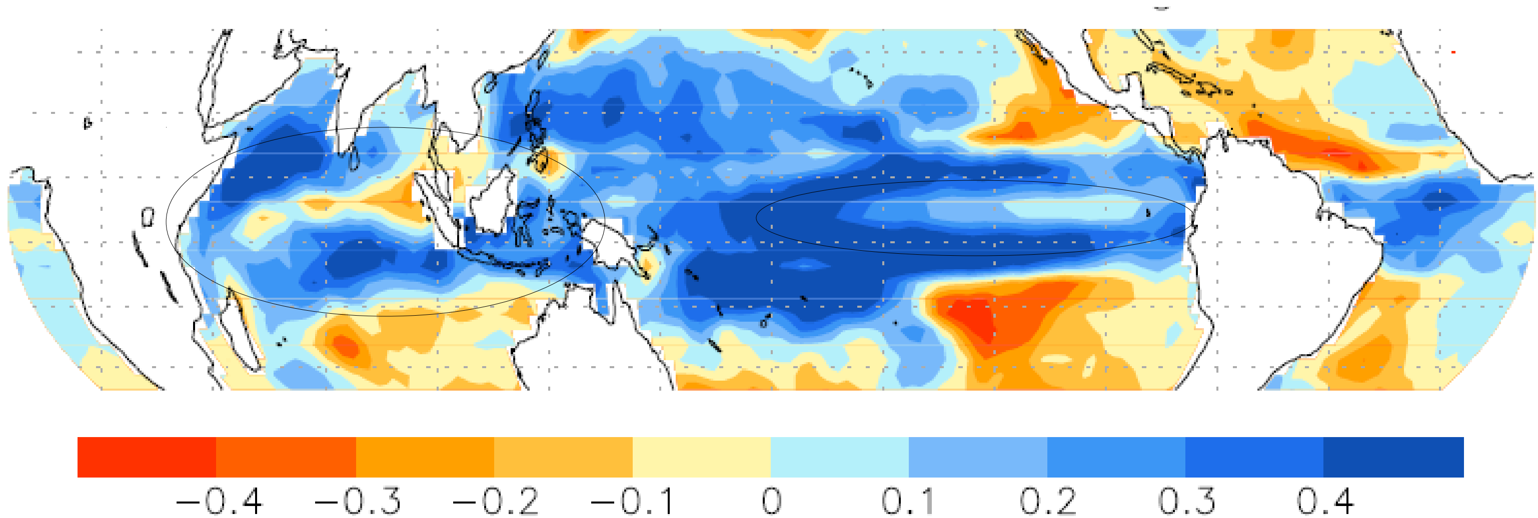
$$\Delta P/\Delta T_s = (\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha})/\Delta T_s$$

- "Rich get richer"
- In convective regimes : dP/dTs close to Clausius-Clapeyron
- Sign of dP/dTs robust in convective regions, less in subsidence regimes

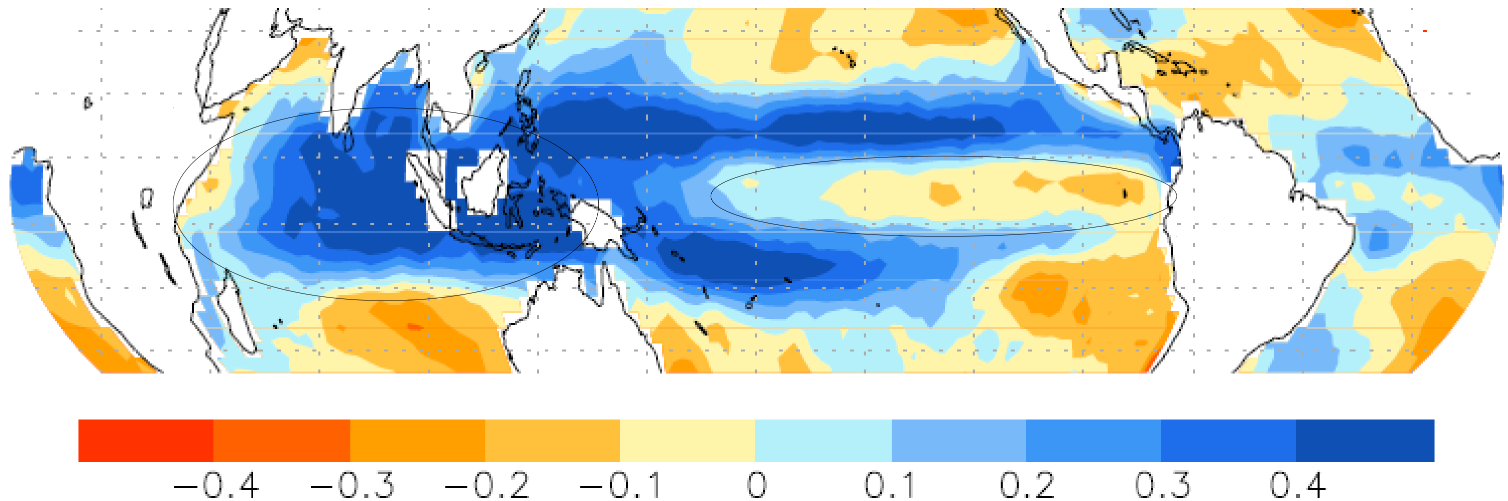


Mean precipitation change predicted by CMIP3 models (1pctCO2)

$$\Delta P$$



$$\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha}$$

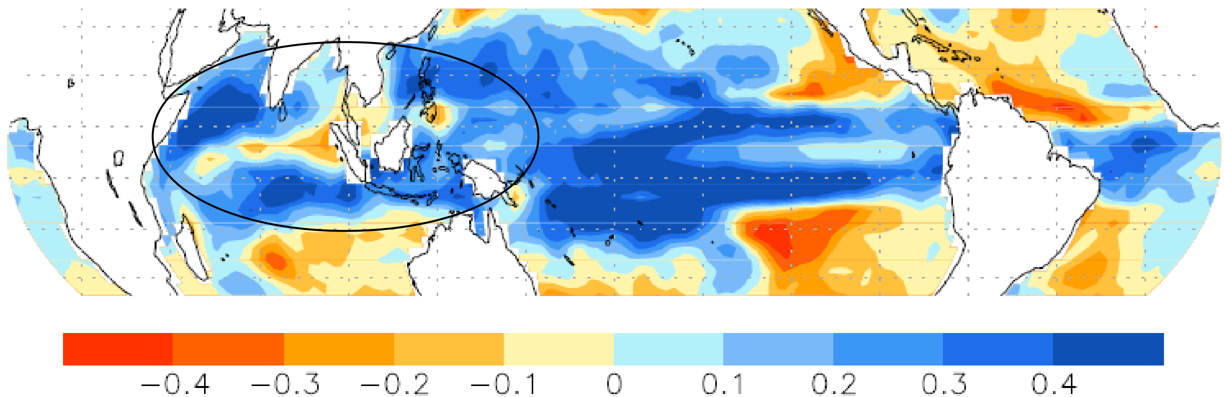


-> Dynamical component ?

Mean precipitation change predicted by CMIP3 models (1pctCO2)

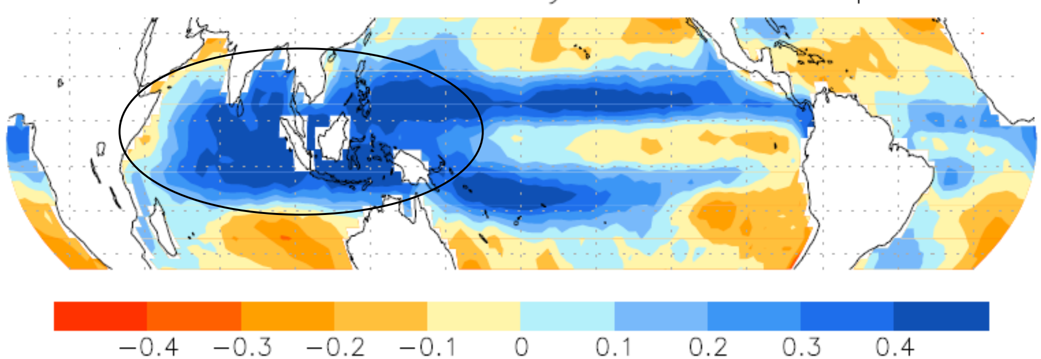
$$\Delta P = \Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha} + \Gamma_q \Delta\overline{\omega}$$

CMIP3 deltaP: total change

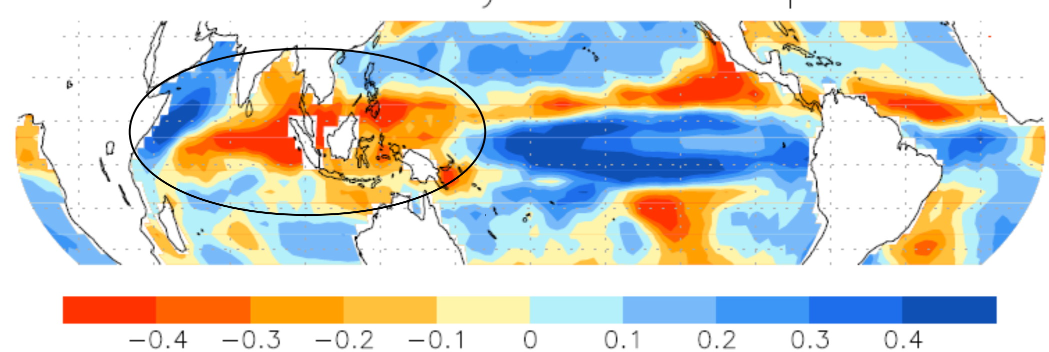


$$\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha} \quad + \quad \Gamma_q \Delta\overline{\omega}$$

CMIP3 deltaP: thermodynamical component



CMIP3 deltaP: dynamical component



→ Interpretation of dynamical changes ?
Role of ACRF changes ?

Moist Static Energy budget $(h = C_pT + gz + Lq)$:

$$F_s + R_{clr} + \overline{\omega}\,\Gamma_h + H_h + V_h^{\alpha} + ACRF = 0 \;\; with \;\; \Gamma_h = \left[\psi\,\frac{\partial h}{\partial P}\right]$$

$$\rightarrow \quad \overline{\omega} = -\frac{F_s + R_{clr} + H_h + V_h^{\alpha} + ACRF}{\left[\psi\,\frac{\partial h}{\partial P}\right]} = -\frac{Q + ACRF}{\Gamma_h}$$

Dynamical component of ΔP :

$$\Gamma_q \Delta\overline{\omega} = -\frac{\Gamma_q}{\Gamma_h}\left(\overline{\omega}\,\Delta\Gamma_h + \Delta Q\right) - \frac{\Gamma_q}{\Gamma_h}\,\Delta ACRF$$

There are regions where the dynamical change in precipitation turns out to be dominated by a cloud-radiative-dynamical feedback

e.g. Indian Ocean, eastern equatorial Pacific, tropical Atlantic

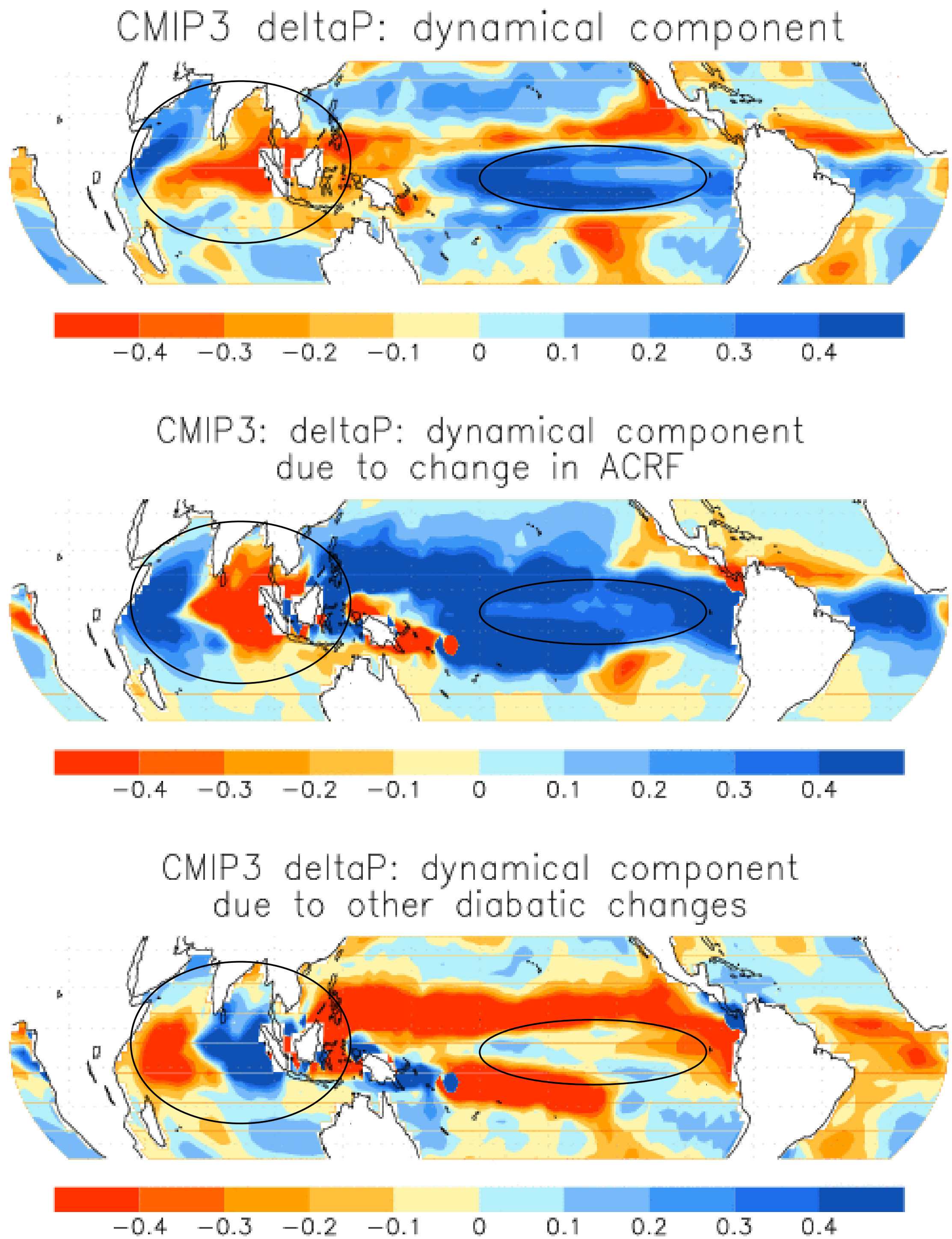
$$\Gamma_q \Delta\overline{\omega}$$

$$=$$

$$-\frac{\Gamma_q}{\Gamma_h}\,\Delta ACRF$$

$$+$$

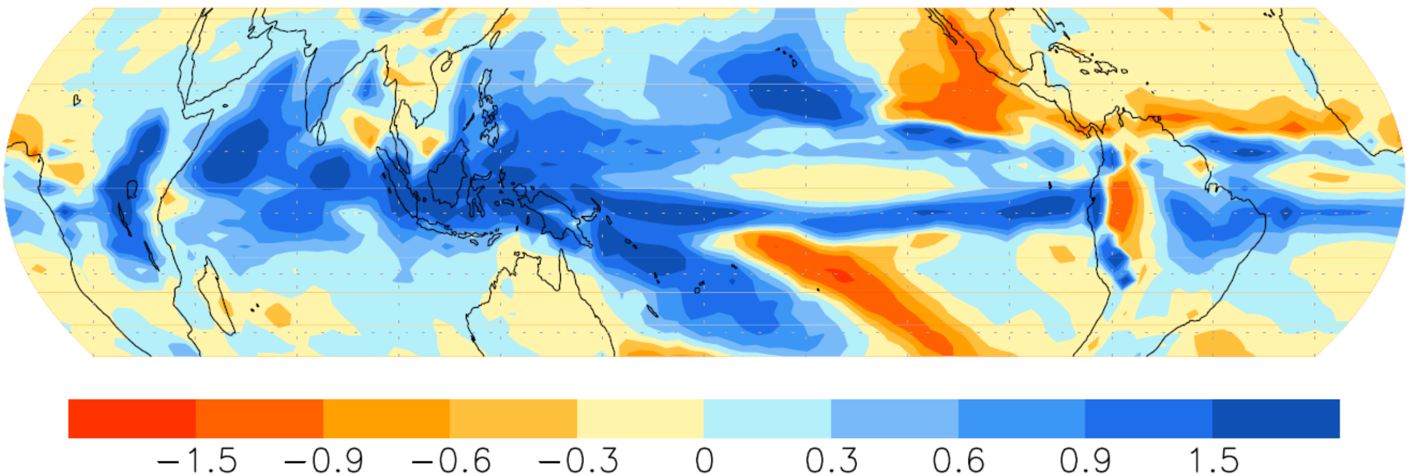
$$-\frac{\Gamma_q}{\Gamma_h}\,(\overline{\omega}\,\Delta\Gamma_h + \Delta Q)$$



CMIP5 IPSL-CM5-LR OAGCM :

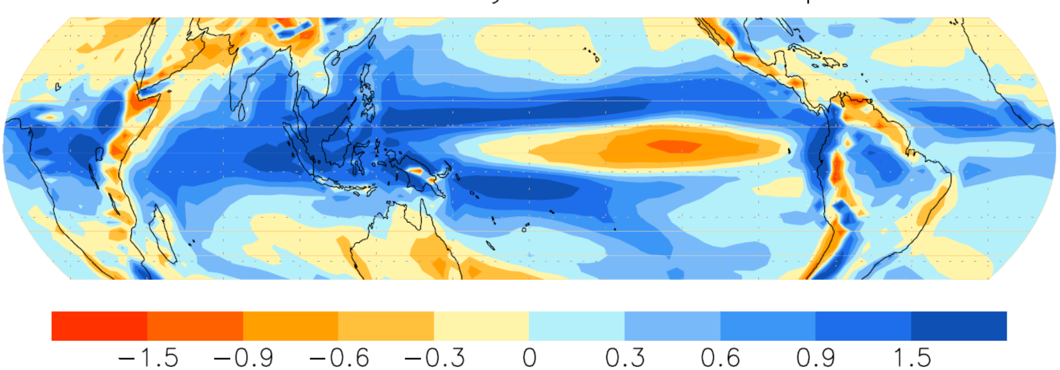
$$\Delta P = \Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha} + \Gamma_q \Delta\overline{\omega}$$

delta P: total change



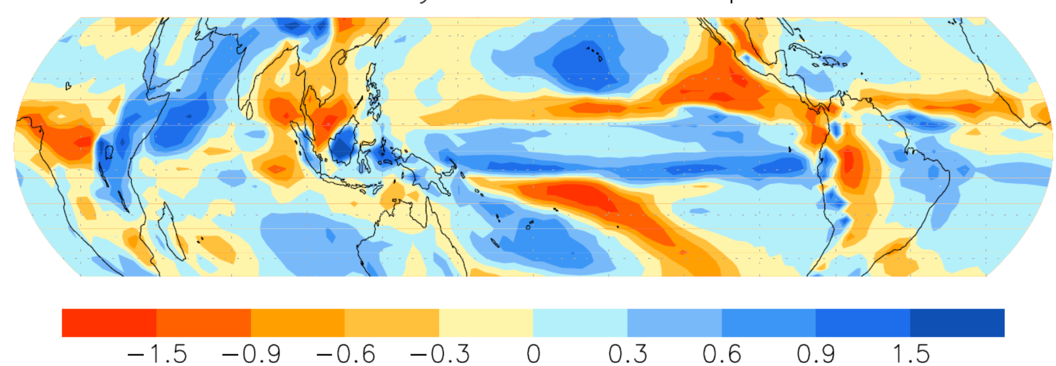
$$\Delta E + \overline{\omega}\,\Delta\Gamma_q + \Delta H_q + \Delta V_q^{\alpha}$$

delta P: thermodynamical component



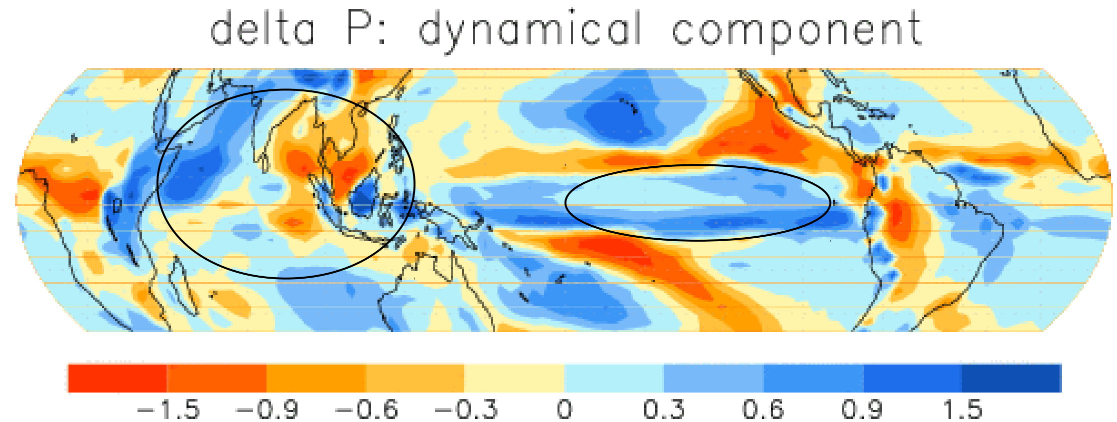
$$\Gamma_q \Delta\overline{\omega}$$

delta P: dynamical component



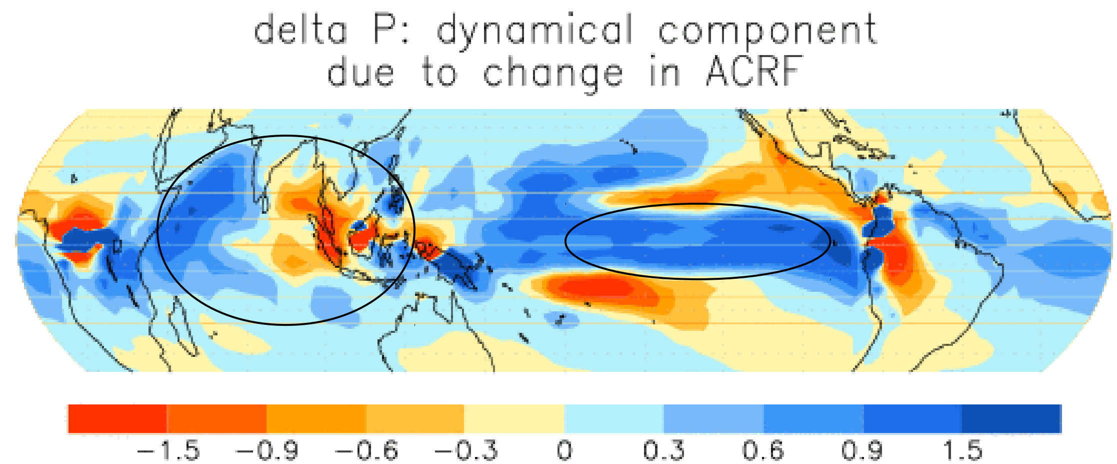
Similar results found for CMIP5 IPSL-CM5A-LR OAGCM

$$\Gamma_q \Delta \overline{\omega}$$



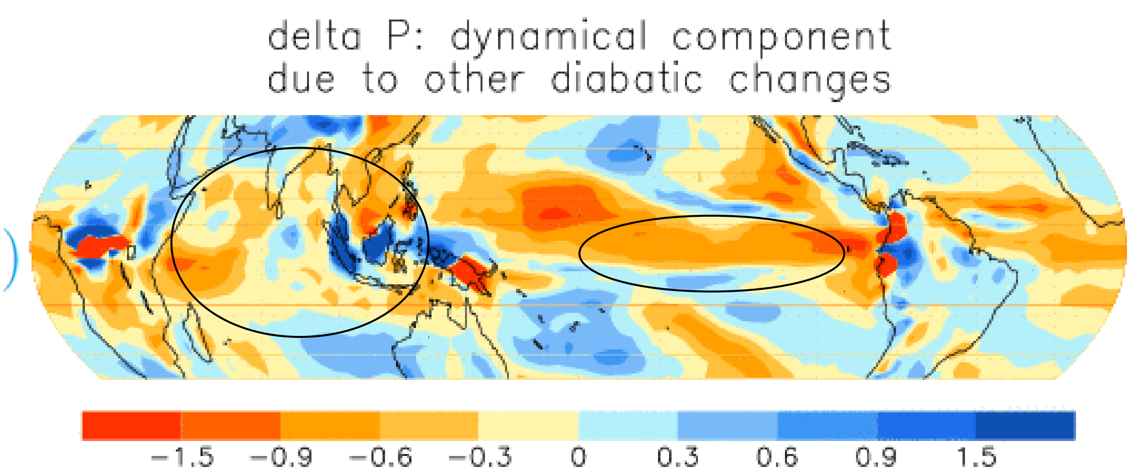
=

$$-\frac{\Gamma_q}{\Gamma_h} \Delta ACRF$$



+

$$-\frac{\Gamma_q}{\Gamma_h} \left(\overline{\omega}\, \Delta \Gamma_h + \Delta Q\right)$$



Conclusion

- A methodology is proposed to analyze regional dynamical and precipitation changes in GCMs (or in observations).

- It makes it possible to assess quantitatively the contribution of ACRF changes to regional changes in the large-scale vertical motion of the atmosphere.

- Its application to CMIP3 models suggests that in some regions, ACRF changes play a substantial or even dominant role in regional precipitation changes, especially in equatorial regions.

- The response of cloud-radiative effects to global warming thus matters for much more than just climate sensitivity.

- The aim is now to apply this analysis to CMIP5 models to better understand the origin of robust and non-robust responses of clouds and precipitation to climate change.


Thank You !